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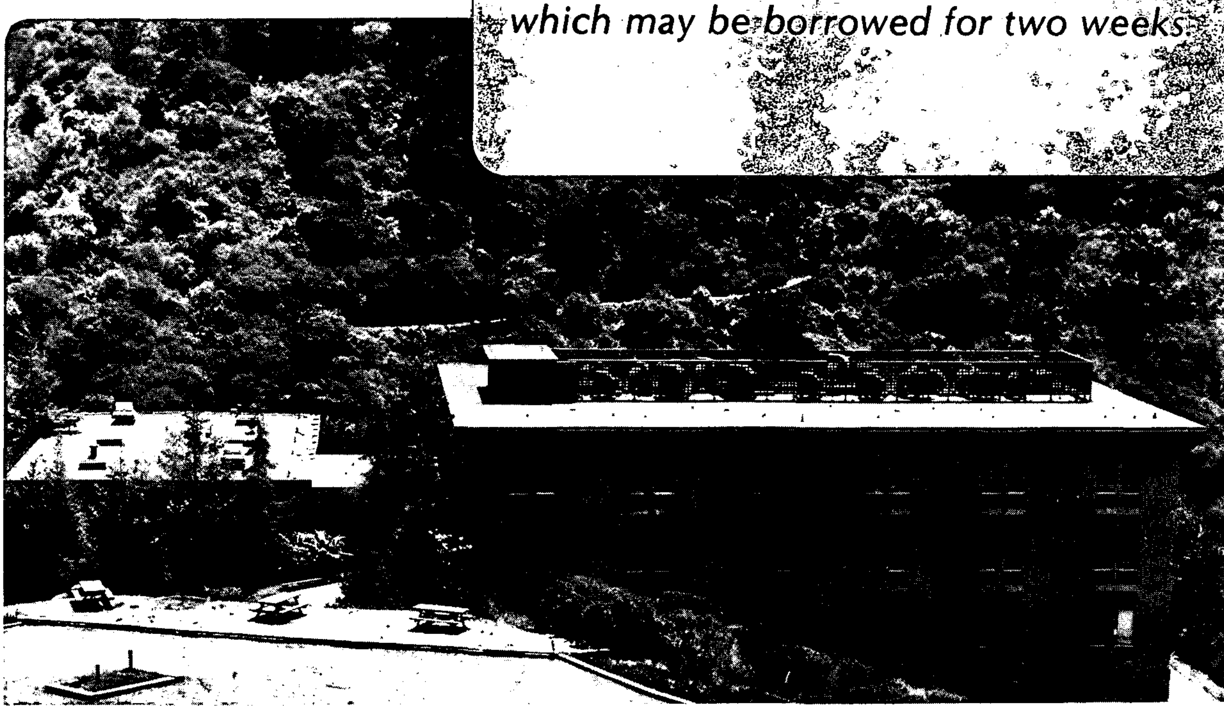

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DISCLAIMER

TEM INVESTIGATION OF POLAR-ON-NONPOLAR EPITAXY: GaAs-AlGaAs on (100) Ge

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ABSTRACT

Morphologically excellent GaAs and AlGaAs epitaxial layers have been grown on (100) Ge substrates by molecular-beam epitaxy (MBE). Transmission electron-microscope (TEM) studies of the thin-film cross sections revealed that defects, most probably antiphase domains, were contained within a 20–30 nm thick initial layer near the GaAs/Ge interface, formed with a 0.1-μm/h growth rate at 500°C. A reduction of defects occurred in the remaining 0.1-μm thick layer, for which the growth rate and temperature had been increased to 1 μm/h and 580°C, respectively. The interface between this GaAs layer and a subsequently grown 35-nm thick AlAs film was found to undulate with a period of 150–200 nm and an amplitude of 5–10 nm. Such large undulations were not observed in AlGaAs-GaAs superlattices grown after an additional deposition of 2-μm GaAs. High-resolution electron-microscopy observations suggest that transitions between different layers are abrupt on the atomic scale. In addition, modulation-doped field-effect transistors fabricated on these layers had similar characteristics to those obtained with MBE layers grown on GaAs substrates. These results demonstrate that the (100) Ge surface is suitable for MBE polar-on-nonpolar semiconductor growth and that the integration of III-V films with silicon electronic devices via epitaxial Ge on Si is feasible, provided that epitaxial Ge of sufficient quality grown on Si is available.

INTRODUCTION

The growth of III-V compound semiconductor films on nonpolar substrates is of considerable interest, because of the potential application of these films for electronic and optoelectronic devices. These applications include GaAs solar cells [1], heterojunction bipolar transistor [2], light-emitting diodes [3], and modulation-doped field-effect transistors (MODFETs) [4,5]. The growth of GaAs and AlGaAs films on Si substrates is especially interesting because of their good mechanical strength and low cost. In addition, such a substrate would allow monolithic integration of III-V electronic devices with well-established Si technology. However, two materials problems, antiphase domain formation and large (~4%) lattice mismatch [6–8], have to be overcome in order to successfully use Si substrates. A possible solution to the problem involves epitaxial growth of Ge (which has a small, ~0.1%, lattice mismatch with GaAs) on Si followed by epitaxial growth of the III-V film, or epitaxial growth of well-matched GaP or AlP films followed by graded transition to GaAs or AlAs. In both cases the greatest concern would be elimination of antiphase domains. These domains may be formed by coalescence of islands of As and Ge when epitaxial growth begins on the nonpolar semiconductor surface, or, more probably, they may be caused by the existence of monatomic steps on the substrate. These two possibilities are schematically illustrated in Figs. 1a and 1b, respectively.

In this work molecular-beam epitaxy (MBE) GaAs-AlGaAs layers have been grown on (100) Ge substrates in order to determine the viability of the first approach to solving the

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problem described above. The quality of the films and their interfaces have been studied by transmission electron microscopy and by the characteristics of electronic devices fabricated on these layers.

EXPERIMENTAL PROCEDURES

The III-V compound semiconductor layers were grown by MBE on (100)2° [011] oriented heavily doped p-type Ge. The substrates were first degreased in boiling trichloroethane, acetone, methanol, and water. They were then etched for 20 min in H_2SO_4:H_2O_2:H_2O (5:1:1), rinsed in deionized H_2O, and dried with N_2 gas. The substrates were then mounted to Mo blocks using In solder, loaded into the MBE system, outgassed at 630°C (as read by a thermocouple in an auxiliary chamber), and immediately transferred into the growth chamber. Prior to the growth the substrate temperature was raised to 600°C and then lowered to 500°C. Following the procedure [7], an As prelayer was deposited, followed by 250 Å of GaAs growth with a large As overpressure and the growth rate 0.1 μm/h. The growth rate and substrate temperature were then increased to 1 μm/h and 580°C during the growth of 0.1 μm of GaAs. Different sequences of GaAs and $Al_xGa_{1-x}As$ layers were then deposited. MODFET structures were fabricated from these layers according to procedures described elsewhere [5]. Cross-sectional TEM specimens with <011> foil surface orientation were prepared using the same procedures as for cross-sectional Si specimens [9]. The observations were performed at 200 kV and 100 kV in JEOL 200CX and Philips 301 electron microscopes, respectively.

EXPERIMENTAL RESULTS

TEM Results

Figures 2a and 2b show a TEM cross section of one of the MBE-grown layers and the sequence and thickness of the deposited layers, respectively. The morphology of the growth front at the top of the first layer, as revealed by the interface between GaAs and AlAs, is not planar. It undulates with a period of 0.2–0.25 μm and an amplitude of 10–15 nm. Apparently the interface consists of pyramids with facets approximately normal to <116> directions and inclined between 7–12° with respect to a planar Ge/GaAs interface, as can be seen in Fig. 3. Figure 4, which is from a different area of the same specimen, shows in greater detail the defect contrast most probably corresponding to antiphase domains at the Ge/GaAs interface. Tilting experiments did not reveal any defect contrast in other layers. It is tentatively concluded that antiphase domains were contained only within the initial region of growth and that areas further from the Ge/GaAs interface were defect-free. The transition regions between adjacent layers were atomically abrupt, as can be seen from the high-resolution electron micrographs shown in Fig. 5 and Fig. 6. The GaAs/Ge interface had good matching of the lattice planes on the two sides of the interface, as expected for materials with close lattice parameters. No contrast corresponding to antiphase boundaries was observed at this level of resolution, in agreement with earlier computer simulation [10]. The GaAs lattice planes continue across the AlAs layer, which is about 500 Å thick, although some AlAs, especially near the TEM specimen edge, appeared to be amorphous (probably due to rapid oxidation in the atmosphere enhanced by condensation of water vapor on the specimen after removal from the cold-stage ion mill). In the thicker regions of the specimen (Fig. 6), the lattice planes also continued across the AlAs layer, suggesting that the material was crystalline before it oxidized.

An additional interesting growth feature of these MBE layers was revealed in the bright-field image in Fig. 7, which shows a reduction of the undulation of the growth front 2 μm above the AlAs layer. This is illustrated by the flat layers of the superlattice 40× (100 Å $Al_{.25}Ga_{.75}As$/150 Å GaAs). The transition between the GaAs and $Al_{.25}Ga_{.75}As$ layers is shown in the high-resolution micrograph (Fig. 8). The contrast between layers is

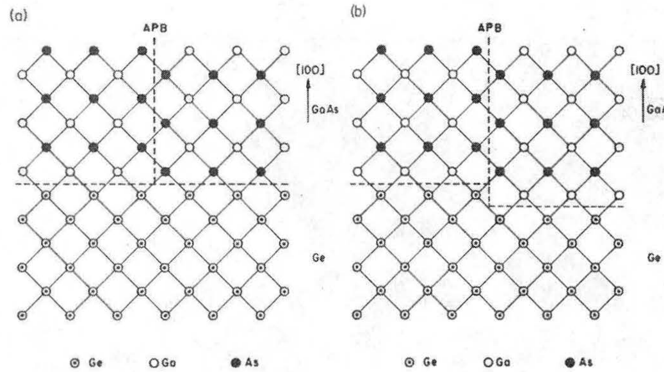
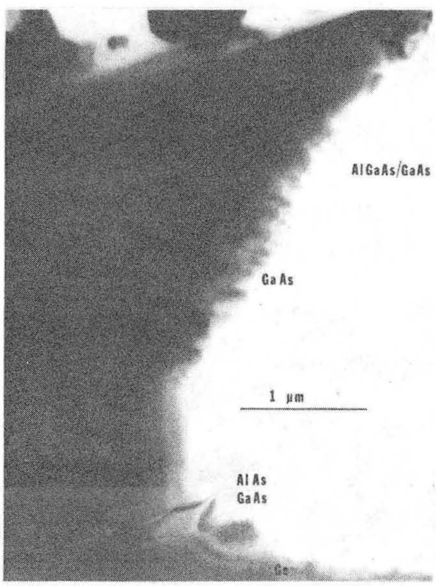


Fig. 1. Possible origin of antiphase boundaries: a) initiated on a flat surface of Ge; b) on a surface containing a monatomic step.



50 Å GaAs (Si)
350 Å $Al_{.3}Ga_{.7}As$ (Si)
30 Å $Al_{.3}Ga_{.7}As$
40 × (150Å GaAs/100Å $Al_{.25}Ga_{.75}As$)
2 μm GaAs
500 Å AlAs
0.1 μ GaAs
250 Å GaAs slow growth
(100) Ge substrate

Fig. 2. The structure of the films grown on (100) Ge: a) TEM cross section; b) corresponding schematic of the MBE layers.

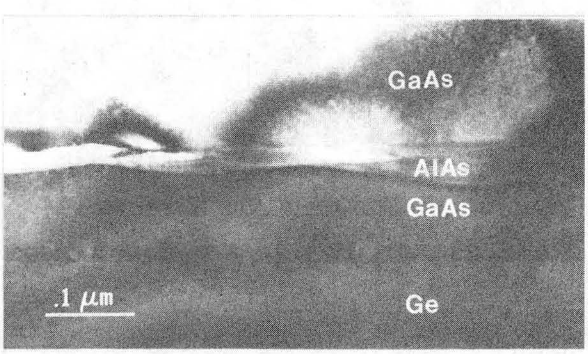


Fig. 3. TEM image of the initial layers demonstrating undulation of the MBE growth front.

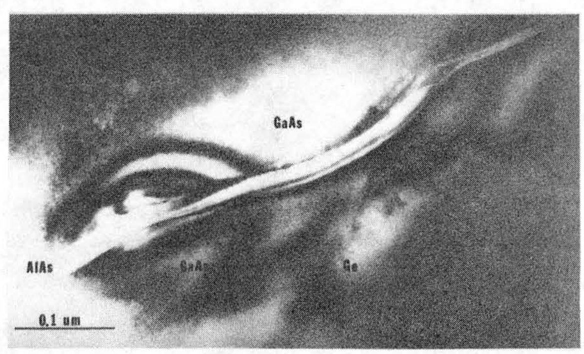


Fig. 4. Defects near the Ge/GaAs interface, most probably antiphase boundaries.

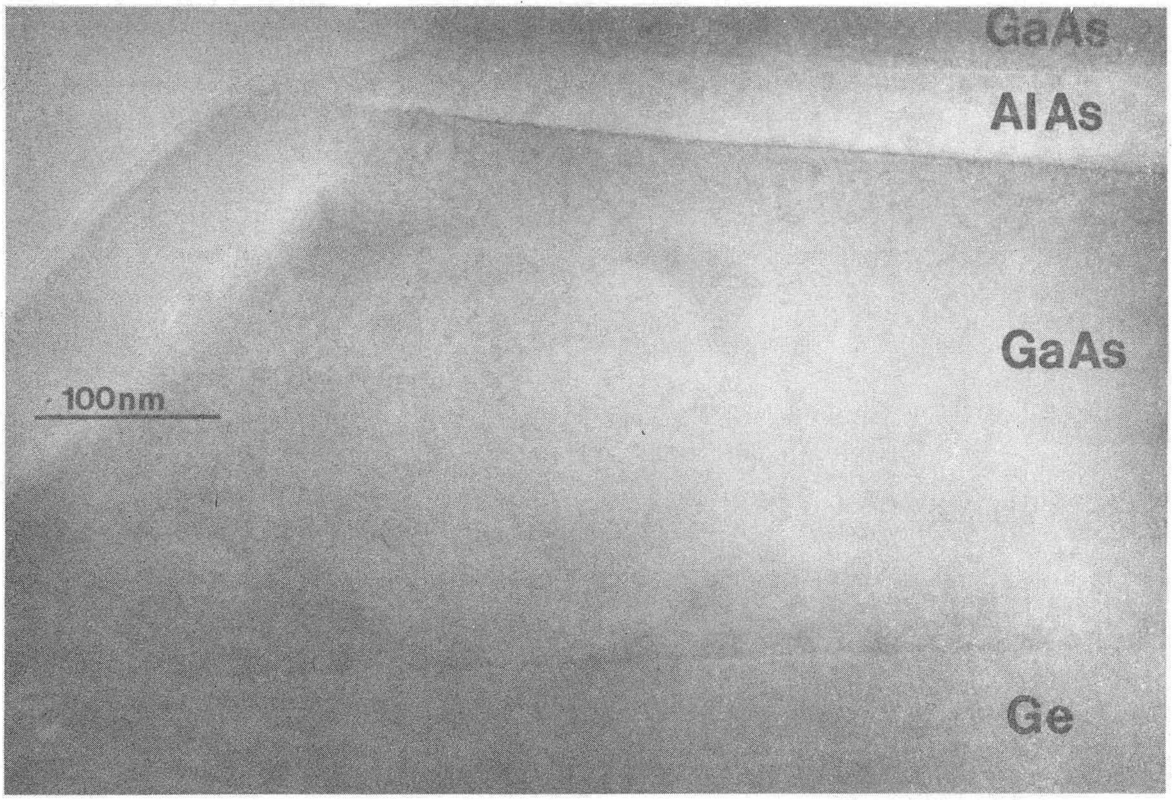


Fig. 5. High resolution image of Ge/GaAs, GaAs/AlAs interfaces.

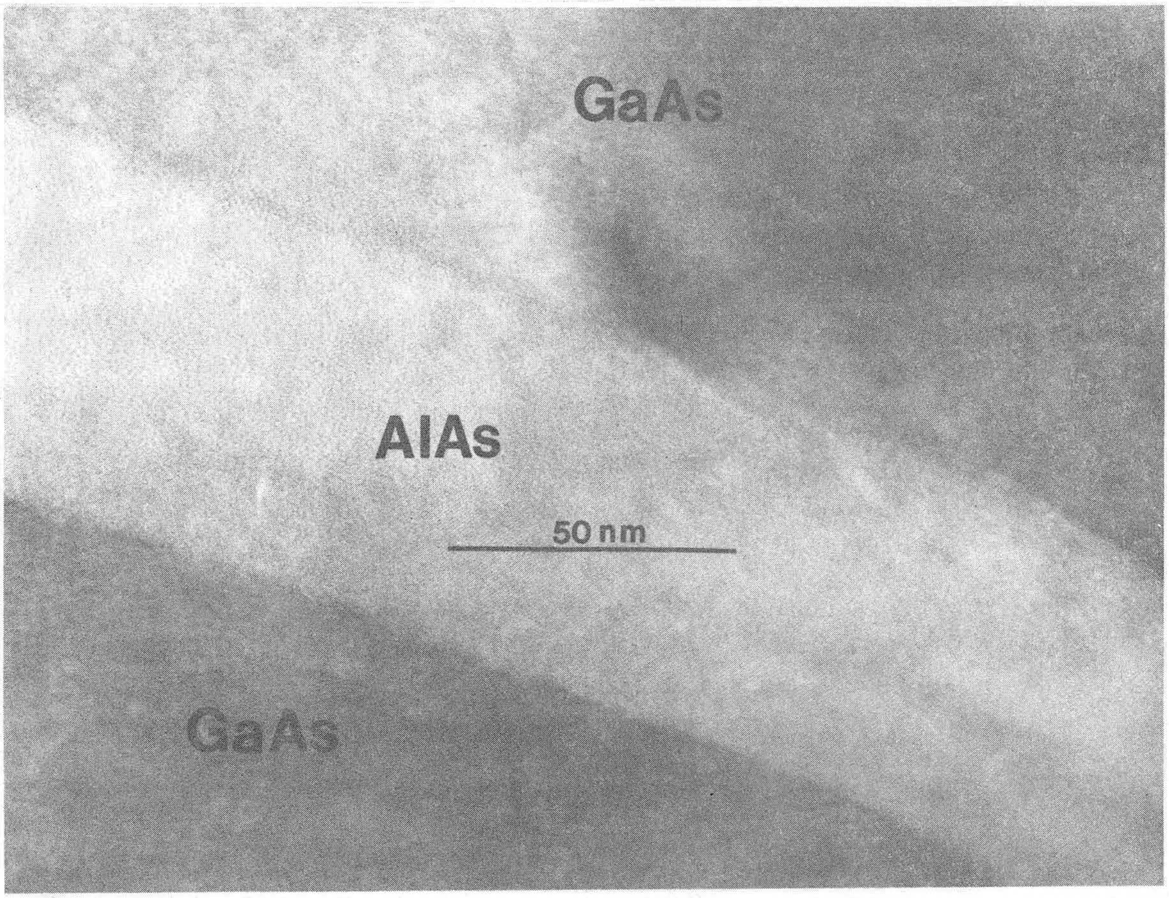


Fig. 6. High resolution image of GaAs/AlAs/GaAs showing continuity of lattice planes.

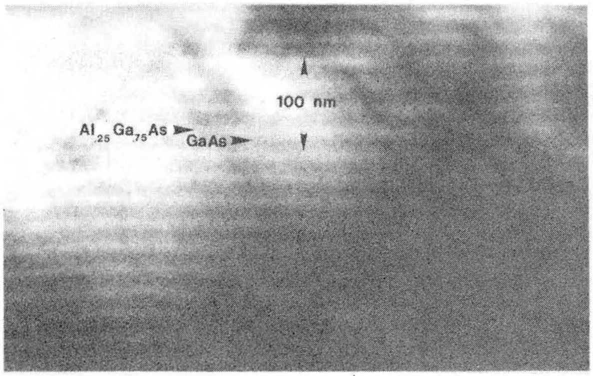


Fig. 7. Bright field image of superlattices with g = [200].

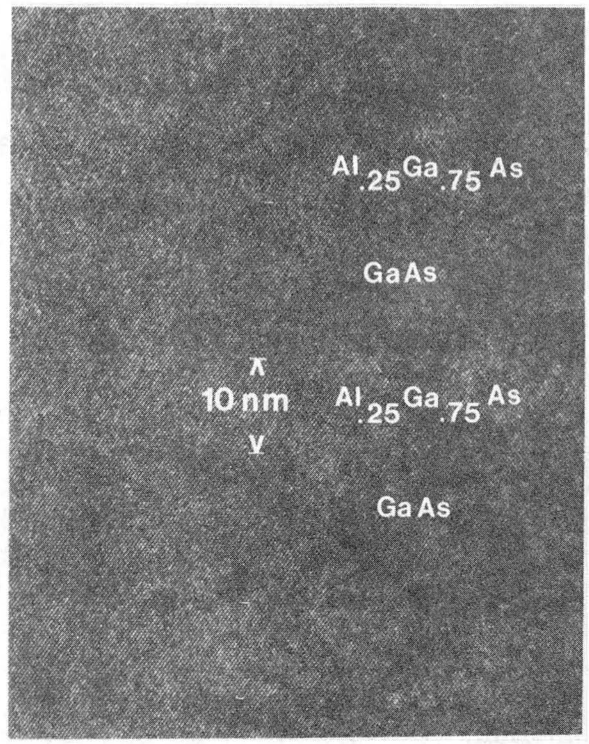


Fig. 8. High resolution image of superlattices.

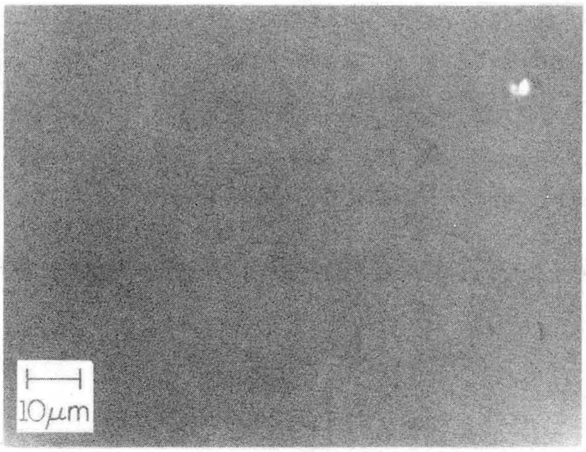


Fig. 9. Surface morphology as revealed by Nomarski phase-contrast microscopy.

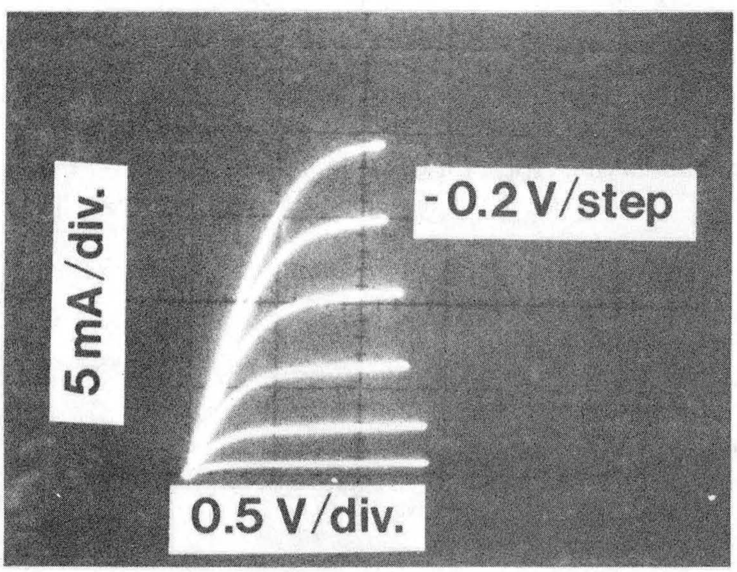


Fig. 10. MODFET I-V characteristics.

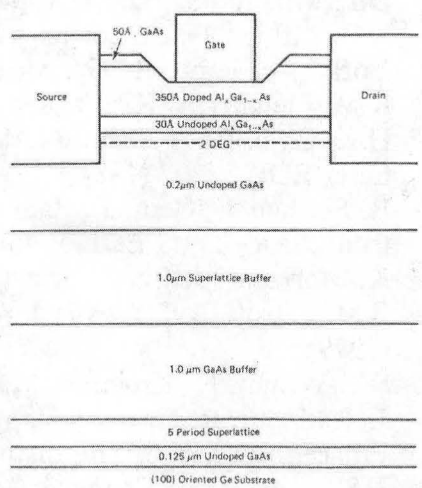


Fig. 11. MODFET structure.

due to the different atomic-scattering factor between GaAs and AlGaAs with Al randomly substituted in the Ga sublattice. This transition is abrupt on the atomic scale. Therefore, it is not surprising that the morphology of the surface as revealed by the Nomarski phase-contrast method is very good, as shown in Fig. 9. The surface flatness compares well with the surfaces of similar films grown on (100) GaAs substrates.

Characteristics of MODFETs

Modulation-doped field-effect transistors were fabricated on the layers described above using procedures described elsewhere [5]. The 300 K I-V characteristics shown in Fig. 10, were obtained from devices with $1\times 145\ \mu m$ gates and $3\mu m$ source drain spacing fabricated from structures with the layer arrangement shown schematically in Fig. 11. The measured transconductance of the device was 160 mS/mm, and the output conductance was 3.6 mS/mm, which is comparable to results obtained from MODFETs grown on GaAs. The threshold voltage of the device shown in Fig. 11 was −0.95 V. When cooled to 77 K, the transconductance increased to 345 mS/mm, indicating existence of high-saturation-velocity two-dimensional electron gas (2-DEG). The output conductance at 77 K reduced to 2 mS/mm. The absence of looping in the I-V characteristics in Fig. 11 and the high transconductances demonstrate the high quality of the GaAs/AlGaAs grown on the Ge (100) substrates.

CONCLUSIONS

TEM studies of GaAs and GaAlAs thin films grown on (100) Ge substrates showed excellent crystalline perfection. MODFETs fabricated on these layers had characteristics similar to those obtained on MBE layers grown on GaAs substrates. These results indicate that monolithic integration of III-V and Si electronic devices on Si substrates is feasible, provided that epitaxial Ge of sufficient quality can be grown on Si.

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